Model Based Engineering Support for Future Attack Reconnaissance Aircraft: Final Report

May 2024

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1. Scope and Purpose

This is the final report for Model-Based Engineering Tools for an Affordable Lifecycle – Vertical (METAL-V) delivery order 12 (DO12). This contract's period of performance began 14 April 2023. This report describes our progress through February, 2024. Note that Galois also supported Open Systems Verification Demonstration (OSVD) effort under a prior task, METAL-V DO11, for which we have submitted an additional separate final report.

Galois's primary focus for this task order was support of the OSVD 1 and OSVD 2 efforts. We additionally supported several working groups and efforts which contributed to the Future Attack and Reconnaissance Aircraft (FARA) Model-Based Systems Engineering (MBSE) environment and capabilities.

Although the FARA Program was ultimately cancelled, we contributed to significant progress of the state of the art for evaluation of Modular Open Systems Approach (MOSA) methodologies, artifacts, and systems. This report will describe Galois's contributions to the OSVD efforts, the FARA digital engineering environment, and to the state of the art for MBSE. We gained a wealth of information about MBSE and acquisition, lessons that we describe in this report.

OSVD pioneered a methodology to assess and verify that a performer contractor's system has satisfied the MOSA mandate per the National Defense Authority Act (NDAA 2018 and 2021). This method can be adapted and applied to other programs. This report will identify lessons-learned and recommendations for future use of the OSVD methodology on other programs. This report is intended to provide a case study for future efforts that aim to incorporate digital engineering, MBSE, or Architecture Centric Virtual Integration Process (ACVIP). This report provides examples and recommendations that will aid decision makers by providing patterns to follow, grounded examples of challenges we encountered, and recommendations for effective application of these methods.

This report is a redacted version for public release approval. The details of this report have no attribution to specific performer contractor information which is contained in the original final report.

2. Bottom Line Up Front

The central conclusions of this effort are that model-based methods for procurement and systems integration are effective for improving systems engineering outcomes; model-based methods identified many of the risks that were manifested in the lab. Most of the time or capability-loss issues encountered in the lab were related either to software configuration or network configuration. We demonstrated a workable path to successful application of MBSE and ACVIP for major embedded systems integration activities. We observed successful adoption and application of MBSE and ACVIP by FARA performers and successfully applied performer-generated ACVIP artifacts. Galois's role in OSVD allowed us to contribute model-based risk virtual integration assessments to help reduce risk for physical integration efforts. By applying ACVIP to OSVD, we were able to correctly predict integration risks that were later realized in lab activities (specifically network configuration errors). In this case, we found that the best predictor of problems in physical asset integration was *ambiguity* rather than *incompatibility*, in design artifacts. The key remaining challenges for broad realization of the benefits of MBSE and ACVIP are dealing with culture change and scalable deployment of digital engineering environments across organizational boundaries.

3. Context

The FARA program was cancelled on 8 February 2024 because of top-level Army strategic change away from human-piloted to uncrewed reconnaissance in a changing conflict landscape. Until its cancellation, FARA was a pathfinder program for digital engineering practices from which the rest of the Army could learn and grow. The FARA performers, Bell Textron and Sikorsky, leaned into FARA's pathfinding efforts and contributed immensely to positive outcomes and discoveries that will benefit many programs to come.

We are learning from the battlefield—especially in Ukraine—that aerial reconnaissance has fundamentally changed ... Sensors and weapons mounted on a variety of unmanned systems and in space are more ubiquitous, further reaching, and more inexpensive than ever before.
- Chief of Staff of the Army Gen. Randy George on the Cancellation of FARA[1]

Adventium Labs, which merged with Galois Inc. (Galois) in late 2022, was fortunate to be part of FARA for many years, beginning with FARA's inception and growth out of Joint Multi-Role Mission System Architecture Demonstration (JMR MSAD) to its realization as a full-scale acquisition program. Galois's role as FARA ACVIP and MBSE Subject Matter Experts (SMEs) gave us a unique perspective from which to contribute to and learn from FARA.

FARA was different from traditional acquisition programs in several ways. FARA and its sister Future Long Range Assault Aircraft (FLRAA) included technologies and methods born out of a renewed Department of Defense (DoD) emphasis on modularity, as dictated by the law[2] and realized through new and emerging standards like Future Airborne Capability Environment (FACE™), and Sensor Open Systems Architecture (SOSA™). FARA employed a model-based architecture framework (the FAF), which was deployed and refined at enterprise Family of Systems (FVL), organization (FARA), and platform system architecture design (i.e. FARA Performer) levels. FARA applied a novel Other Transition Authority (OTA) for Prototype (OTAP) contract to solicit frequent deliveries of model-based artifacts from FARA performers. FARA employed a novel Open Systems Verification Demonstration (OSVD) activity to verify and validate performers' Modular Open Systems Approaches (MOSAs).

Between April 2023 and February 2024, under contract W911W6-17-D-0003 task orders W911W6-22-F-703C (DO11) and W911W623F703A (DO12), Galois supported the FARA

[1] https://militaryembedded.com/avionics/computers/fara-discontinued-as-us-army-overhauls-aviation-plan
[2] United States law. NDAA for Fiscal Year 2021 section 804, NDAA for Fiscal Year 2017 section 805

program in general and specifically supported the FARA OSVD by conducting virtual integration in support of the Army Combat Capabilities Development Command (DEVCOM) Aviation & Missile Center (AvMC) Software, Simulation, Systems Engineering and Integration (S3I) Directorate[3], which acted as the Third Party Integrator (TPI) for the FARA OSVD. This time frame and the associated activities are the focus of this report. Galois submitted a separate report describing task DO11 in detail, but this report is a retrospective on FARA OSVD overall, and as such lessons learned during DO11 are included (minus any performer attributable information in this publicly released version of the report).

OSVD assumes that a system which sufficiently implements a MOSA will be modifiable by a qualified third party without direct involvement by the original manufacturer of the system. The OSVD verified FARA performer's modularity by assigning a TPI to modify the performer system without direct assistance from the performer.

The OSVD methodology (described in detail in reports from S3I) describes a method to determine the modularity of a System Under Assessment (SUA) by using a TPI to change the system configuration without involvement from the system manufacturer (i.e., the performer contractor). This methodology, and the associated scoring systems used to evaluate FARA Performers' status with respect to MOSA, are described in reports from S3I (DEVCOM AvMC S3I Directorate - Bell Team, 2023) (DEVCOM AvMC S3I Directorate - Sikorsky Team, 2023). We contributed to this assessment by evaluating the TDPs provided by each performer and (1) assessing the TDPs for completeness and correctness, contributing to the metrics assembled by S3I and (2) evaluating the planned system change against the TDP to identify integration risks.

Working in conjunction with the Carnegie Mellon University Software Engineering Institute (CMU SEI), Galois led the ACVIP strategy and execution for OSVD 1 and OSVD 2. Galois provided numerous ACVIP and MBSE models and reports to the Government throughout the course of this effort, including our virtual integration strategy (via an ACVIP Management Plan), virtually integrated laboratory models (via SysML 1.x and AADL), and risk assessments for OSVD physical integration activities (via per-event and per-performer reports).

In the OSVD activities we found the most likely problems in TPI physical integration were those related to software and network configuration, and the best predictor of problems in TPI physical integration is *ambiguity* rather than *incompatibility* in design. In initial efforts such as JMR MSAD, we and the CMU SEI placed heavy emphasis on automated quantitative and qualitative analyses as the best method for reducing risk. These were valid and valuable but did not find as many risks in OSVD as when we focused on analyses of information (in)sufficiency. A notable second lesson learned through these efforts was that ACVIP should occur early and often during the planning and design process, such that sufficient time exists for risk mitigation (unfortunately on OSVD 1 such time was not available due to tight overall schedule constraints).

In OSVD, some of the risks we identified using ACVIP were *realized in the lab* (i.e., the problems we predicted came to pass). The ACVIP team's involvement in OSVD was not meant

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[3] When discussing OSVD roles, we refer to S3I as the "TPI Integrator" or "TPI." When discussing publications or contributions to organizational workflows, we refer to them as S3I.

to be an exercise in validation of ACVIP itself, and as such we did not gather precision or accuracy metrics for ACVIP assessments. However, these results suggest that ACVIP can make significant contributions to integration risk assessments. Sometimes the performer's own ACVIP results hinted at where integration challenges would exist for the TPI.

In the remainder of this report, we discuss the challenges we encountered and our recommendations for future OSVD efforts, the methodology with which Galois approached virtual integration analysis for risk reduction, the timeline and outcomes of specific model-based risk reduction activities, and our contributions to the overall FARA and Army Aviation MBSE ecosystem. We highlight specific lessons learned and recommendations throughout this report. Where possible, we contrast the risks identified via ACVIP analysis with the lab reports provided by the TPI.

4. Challenges and Recommendations

MBSE has been in use for many years (indeed, it was even in use in 1988 in the early stages of the ill-fated Comanche helicopter program (Linden & Team, 2021). Teams of hard-working and well-intentioned engineers and scientists build components independently to pass them back and forth, but often have different impressions of the same piece or describe the same piece in different ways. Simply applying new technologies or languages is insufficient: Teams need to speak the same language. Passing components to one another without context is insufficient: they need to share an environment to understand and interpret the parts. Such concerns were part of the motivation for ACVIP (Boydston, Feiler, Vestal, & Lewis, 2019) (Aerospace Vehicle Systems Institute, 2024)

In this section we introduce the *challenges* and *recommendations* (Table 1 and Table 2) that arose throughout this project. Challenges describe trends in problems and pain points we observed or encountered. Recommendations are suggested approaches future programs should employ. There is not a 1:1 mapping between themes and recommendation, which is why we do not use the same labeling convention for the two. We reference these challenges and recommendations throughout this report and provide additional detail on both throughout this report.

Table 1 Challenges Encountered in Support of FARA and OSVD

Challenge	Description
1-Ambiguity in design artifacts	We consistently encountered situations in which design details were provided in inconsistent levels of detail or via inconsistent representations (such as multiple names for the same hardware in different design artifacts). In OSVD this was particularly true for the software and network configuration.
2- Inefficient Asset exchange	We often encountered delays or limitations sending or receiving design artifacts with collaborators.

Challenge	Description
3-Overlooking the Enabling environment as an artifact	The line between discrete artifacts and tools, computing systems, and technologies is becoming blurry as the Government's goals shift from procuring documentation and physical assets to procuring environments and architectures. Government notions of "procuring an environment" remain under-defined.
4-Delayed culture change	Stakeholders in Government and industry are unaccustomed to tools and workflows that are changing with shifts to MBSE and ACVIP and are slow to adopt new processes.

Table 2 Recommendations Based on our Experiences Supporting FARA and OSVD

Recommendation	Description
A-Use models for communicating	Well-defined models provide a grounded lexicon for communicating about designs and plans. Communication based on such models is more effective. Use models to communicate information about software and network configuration, both of which were pain points in this OSVD.
B-Invest in accessible infrastructure	Galois and other collaborators were significantly encumbered by limited access to computing and design environments.
C-Plan time for virtual activities	Model-based risk reduction is only effective if there is sufficient time to conduct model-based activities and to react to findings from such activities. The TPI contributors must collaborate so that they have common understanding and can respond with agility to challenges (e.g., such that the physical integration team can adapt to risks identified by the virtual integration team).
D-Train into culture change	Effective model-based engineering requires learning much more than just a modeling language. There is a hierarchy of skills required, as well as a mindset and cultural shift that must take place.

The FARA program had stakeholders with a wide mix of skill levels, which made productive collaboration between stakeholders difficult. The greatest sources of issues occurred on information exchanges between stakeholders, in which stakeholders had to exchange procedures or artifacts (**Challenge 2**, **Recommendations A, B, C**). This was made more complex in cases for which specialized tools or technologies were required to effectively exercise an asset (**Challenge 3 - Enabling Environment**).

The FARA program used Cameo SysML 1.x (SysML) as its definitive modeling language (**Recommendation A - Communicate via Models**). SysML provides a robust foundational language for collaboration between stakeholders and allows extensive references and associations between artifacts from multiple stakeholders. In contrast, PowerPoint-based diagrams are easy to create and require minimal training but are easy to create incorrectly or apply inconsistently (**Challenges 1, 4**).

However, in practice these SysML models proved difficult for many stakeholders to create or exchange and require training to interpret, leading some to fall back to creating PowerPoint-based artifacts to describe designs or plans. For example, the Government and TPI documented the plan for the OSVD 1 activities in PowerPoint, rather than SysML. This was a ready source of errors (**Recommendation D - Training**) due to ambiguities. For example, a PowerPoint diagram used for describing the Eval 1 scenario for used different names for the devices and software described in the SysML models. For OSVD 2 the Government and TPI switched to SysML for planning.

FARA performers used SysML for some aspects of their work, but used additional artifacts instead of, or in addition to SysML, that resulted in sometimes using inconsistent names for the same items across artifacts (**Challenge 1 - Ambiguity**). For example, a FARA performer expressed information about network connections in SysML with one set of component names, and again in a configuration file using a different set of component names. The Galois team had to carefully associate the namespaces of the artifacts to do their work.

The FARA program and its performers additionally adopted standards like Future Airborne Capability Environment (FACE^{TM}) and Architecture Analysis and Design Language (AADL). These standards provide additional semantic precision and consistency beyond what is feasible with SysML (**Recommendation A - Communicate via Models**). Such languages support automated integration analysis, code generation, and consistency validation. However, we experienced some challenges in inconsistent application of these standards across modeling languages.

The FARA program office, TPI, both performers, and all three SME support contractors (Galois, CMU SEI, and Jovian Software Consulting) each had their own digital engineering environment. This meant any time an artifact had to be passed from one organization to another, it had to traverse at least one, and often two or more, organizational boundaries (**Challenge 3, Recommendation B**). Delays in these exchanges negatively impacted an already constrained schedule (**Recommendation C - Plan Time for Change**).

The most valuable applications of MBSE occurred when the team collectively used models to plan the integration (making the model their common language) (**Recommendation A - Communicate via Models**). Maximizing the occurrence and impact of such collaborations will require overcoming these challenges, and we suggest doing so with these recommendations.

5. OSVD MOSA Evaluation Methodology for MBSE Artifacts

Open Systems Verification Demonstration Summary

The FARA program used the OSVD as a method to verify performer adherence to the MOSA mandate.[4] The outcome of the OSVD was to provide evidence that the architecture and design approach of the SUA contribute to system adaptability and to identify any elements of the SUA that are insufficiently adaptable. A full summary of the FARA OSVD is outside of the scope of this report.

[4] See NDAA 2021 section 804.B.iii

The OSVD has three core roles:

- **Government** – The procuring office
- **Performer** – The Original Equipment Manufacturer (OEM)
- **Third Party Integrator (TPI)** – A qualified engineering organization.

The Government sets the objectives of the activities that the TPI is to perform using the OEM provided SUA and associated TDP and an enabling environment. The Government defined these activities by providing integration *scenarios*. The scenarios typically involve changing (i.e., adding, removing, updating, or replacing) some element of the SUA. The FARA OSVD was conducted as a series of events. For each event, the Government set a scenario and set of objectives. The specific roles for FARA OSVD were:

- **Government**: PMO FARA, Supported by the FARA Modeling Team (i.e., Jovian Software Consulting)
- **Performer**: Bell Textron and Sikorsky
- **TPI:** S3I, Supported by the ACVIP Team (i.e., Galois and CMU SEI)

The TPI was responsible for executing the scenario provided by the Government, including planning specific steps for scenario execution, providing necessary hardware and software, physically implementing the scenario, and providing measurements and commentary of the SUA. Galois's role as ACVIP lead was to perform virtual integration in support of the TPI. Galois used the TDP provided by the performer to virtually conduct the activity (change/add/replace) planned by the Government, and to report any findings regarding likely errors or integration challenges.

ACVIP Objectives for OSVD

- Identify what the performer TDP fails to provide for virtual integration (i.e., missing evidence).
- Identify problem areas in the integration model.
- Report two types of results:
    - Defects toward satisfying some requirement (e.g., performance, safety, cybersecurity)
    - Missing specifications in the Integration Model
- Conduct Modeling and Analysis:
    - Integration team: Provide integration model to ACVIP team
    - ACVIP team: Update as needed for translation of SysML or FACE to AADL
    - ACVIP team: Conduct ACVIP analyses to generate reports
    - ACVIP team: Provide measures from analysis reports to the TPI
- Reveal missing evidence:
    - Declared interfaces and interface types can reveal missing connections
    - Declared resource demands/supplies can reveal missing resource dependencies
    - Declared latencies can reveal missing performance specifications
    - Declared behaviors can reveal missing state dependencies
    - Declared data flows can reveal missing flow dependencies

OSVD ACVIP Workflow

We followed a consistent workflow for each performer for each OSVD event, formalized by the OSVD ACVIP Report template we created. The template consisted of the following:

1. Introduction
2. Table of Contents
3. Executive Summary
4. Process
    a. Model Construction
    b. Virtual Integration and Analysis
    c. Identified Risks
5. Evaluation
    a. ACVIP Measures
    b. Performer Model Evaluation
    c. Evaluation of non-modeled artifacts
    d. OSVD Analysis Model Evaluation
6. Recommendations
7. Issues and Resolutions

We followed this workflow eight times (once for each of the two performers for each of OSVD 1 FAM 2, OSVD 1 Eval 1, OSVD 1 Eval 2, and OSVD 2 FAM. We provided reports and models to the Government for these activities (listed in Table 5)

Model Construction

For each OSVD event, in collaboration with the Government and TPI, Galois identified the version of the TDP to use for that evaluation event. We reviewed the contents of the TDP and attended performer-hosted meetings that provided additional detail on the performer modeling approach and changes in the relevant TDP revision from prior versions. To obtain the TDP for each performer we had to use DoD SAFE, as we did not have access to Army data systems (**Challenge 2 - Asset Exchange**).

From our review of the performer TDP we generated a listing (such as that shown in Table 3) enumerating the relevant data in the TDP that could contribute to virtual integration analysis of the OSVD objective.

Table 3 Example TDP Data Sources for ACVIP Assessment from OSVD 1 Eval 2

Information Source	Usage
Baseline Lab Model	Used as the integration model for TPI modifications.
FACE Models	Used to generate AADL models of Unit of Portability (UoP) Software.

Information Source	Usage
Integration Guide	Used as a reference for additional hardware and software properties.
Network Configuration	Used as a reference for latency assessment.

After reviewing the TDP, we selected a model or set of elements from the TDP to use as our baseline laboratory model. We selected the baseline laboratory model based on our understanding of the environment in which the TPI would be required to make a change to the SUA (e.g., at an OEM System Integration Lab (SIL)).

Virtual Integration and Analysis

We started by reviewing the existing ACVIP analysis artifacts and models provided by each performer in their TDP. The performers each conducted independent ACVIP analysis, and we used their analysis artifacts as a starting point for our own analysis. We conducted thorough assessments of the baseline laboratory model and reviewed supplementary information (e.g., any additional textual guides or other non-model artifacts). We created a new SysML model (i.e., an **OSVD Analysis Model**) that extended (via project usage) the performer TDP. We used blocks from the TDP to assemble the OSVD analysis model, extending elements from the TDP when necessary (note that manual propagation of data from non-model artifacts is a source of additional risk).

Based on the integration plan provided by the Government and elaborated by the TPI, the ACVIP team modified the OSVD Analysis Model to mirror the planned changes (i.e., using the OSVD Analysis Model as a "digital twin"). We made changes as described in *Table 4*.

Table 4 ACVIP Analysis Activities as Related to Laboratory Plans

Physical Integration	Virtual Integration using SysML and AADL
"Plug in new hardware."	Declare new hardware connections to system. Update system data flows to include new connections.
"Plug in replacement hardware."	Update existing connections for new hardware. Update system data flows for new hardware.
"Install new software."	Declare new software connections to system. Update system data flows to include new software. Create new bindings of software to hardware.
"Install replacement software."	Update existing software connections to system. Update system data flows to include new software. Update bindings of software to hardware.

Physical Integration	Virtual Integration using SysML and AADL
"Update configuration."	Update system data flows for new configuration. Declare connections to implement new data flows.

Identified Risks

Whenever possible, we collaboratively planned (with the Government and the TPI) what changes to make to the SUA, using the OSVD SysML Analysis model as the "whiteboard" (**Recommendation A - Communicate via Models**). We used these planning sessions to identify technical steps for the TPI, as well as points of ambiguity in the TDP. We found the latter to be predictors of integration problems. We provided risk assessments to the TPI as input to their OSVD event planning (**Challenge 1 - Ambiguity**).

We annotated the OSVD SysML analysis model with properties needed for automated analysis in AADL, such as power, weight, or latency. We analyzed the OSVD laboratory using tools like the SysML to AADL bridge and Curated Access to Model-based Engineering (CAMET) Library Tools.

ACVIP Measures

The OSVD activity included an extensive set of measures against which the TPI used to assess each performer's SUA and TDP for each event. We contributed to the definition of these measures, as well as to the scoring of performer TDPs where ACVIP was relevant. We used Galois's *Model Readiness Report Cards* as the starting point for our measure contributions.

As the intent of the OSVD is to evaluate the flexibility of the SUA, our analysis approach did *not* evaluate the SUA for specific physical or behavioral characteristics (e.g., we did not have a target power usage against which to evaluate the model). Instead, we focused on assessing the *analyzability* of the model, meaning instead of asking "what is the total power usage?" we asked, "is there sufficient information in the TDP to evaluate total power usage?" An answer of "yes" to the latter question meant that the TDP was sufficiently well defined to enable a TPI to conduct virtual integration, which contributes to a successful MOSA. The exception to this was if the performer's ACVIP baseline suggested a problem for the TPI integration (e.g., a planned resources is over-utilized) then we did report that as a potential risk.

Performer Model Evaluation

We evaluated the performer TDP using a spreadsheet of measures provided by the Government. During OSVD 1 we used the Model Readiness Report Cards developed by Galois as a framework for evaluating the TDP, then mapped the results of the report card assessments to the TDP. For OSVD 2 we downscaled our evaluation to just use the measures directly. We searched for information according to the ACVIP Management Plan we developed for the OSVD, which called for several analyses including weight, power, utilization, and latency.

Evaluation of Non-modeled Artifacts

In our evaluation of the performer TDP, we considered both the elements of the SUA that the performer had modeled (e.g., in SysML or AADL) and the elements of the TDP that were not modeled (e.g., user guides). We considered all the available information when determining scores for the performer measurements. We often found information that was spread across multiple representations (e.g., in models and in user guides) and sometimes found information that was inconsistent across representations (e.g., different names for the same physical hardware in a user guide and in a model (**Challenge 1 - Ambiguity**)).

OSVD Analysis Model Evaluation

We searched the following sources in order:

1. **TDP SysML Models**: Starting from the baseline laboratory model, we looked for relevant information to support the analyses. In some cases, the information was included in SysML tags. In other cases, the information was encoded informally (e.g., via names of components). We logged issues for clarification with the OEM when we found conflicting elements seemingly describing the same component.
2. **TDP AADL Models**: The OEMs included some textual AADL models in their TDP, but both OEMs generally described their SysML models as authoritative.
3. **TDP Prose Documentation**: The OEMs included textual documentation (e.g., user guides, Interface Control Documents (ICDs) that had information about properties of components.
4. **TDP Configuration Files:** The OEMs included some plain text configuration files in their TDPs that included relevant data to support analyses.
5. If we could not find the information in these locations, we noted its absence for evaluation/search in future TDPs. **We communicated these gaps to the performers** via the TPI. For specific gaps, see the issues sections of the S3I OSVD 1 Reports, which include our findings.

After finding the relevant information to support weight, power, utilization, and latency analysis, we applied these properties to the OSVD Analysis Model by extending blocks from the TDP, adding AADL stereotypes, and applying AADL property tags. We added end to end data flow information by creating sequence diagrams with AADL flow.

After applying these properties, we used the CAMET Library SysML to AADL Bridge to generate textual AADL models. We ran analysis tools on the generated AADL models and reported the results. However, our objective was to evaluate the analyzability and not the specific analysis results.

OSVD Process Findings

In this section we discuss findings related to the process of conducting OSVD. For each evaluation event, we provided recommendations for ACVIP-relevant measurements to S3I. We provide the outcomes of individual OSVD events and per-performer OSVD conclusions later in this paper.

Model Exchange

We consistently encountered friction associated with exchange of design artifacts between organizations (**Challenge 3 - Enabling Environment**). Each OEM used their own digital engineering environment, which was distinct from the digital engineering environment used by PMO FARA, which was distinct from the digital engineering environment used by the PMO FARA Modeling Team, which was distinct from the digital engineering environment used by the ACVIP team. Any updates to the OEM TDP required multiple transmission steps by multiple parties (see Figure 1). This distribution of data and tools introduced delays, as each environment needed a copy of the relevant tools, and each update to artifacts from each stakeholder required transmitting data between environments, which was costly in terms of staff time. For example, PMO FARA staff had to download each new TDP from each performer, then use DoD SAFE to send the TDP to the FARA PMO modeling team and ACVIP team (see Figure 1).

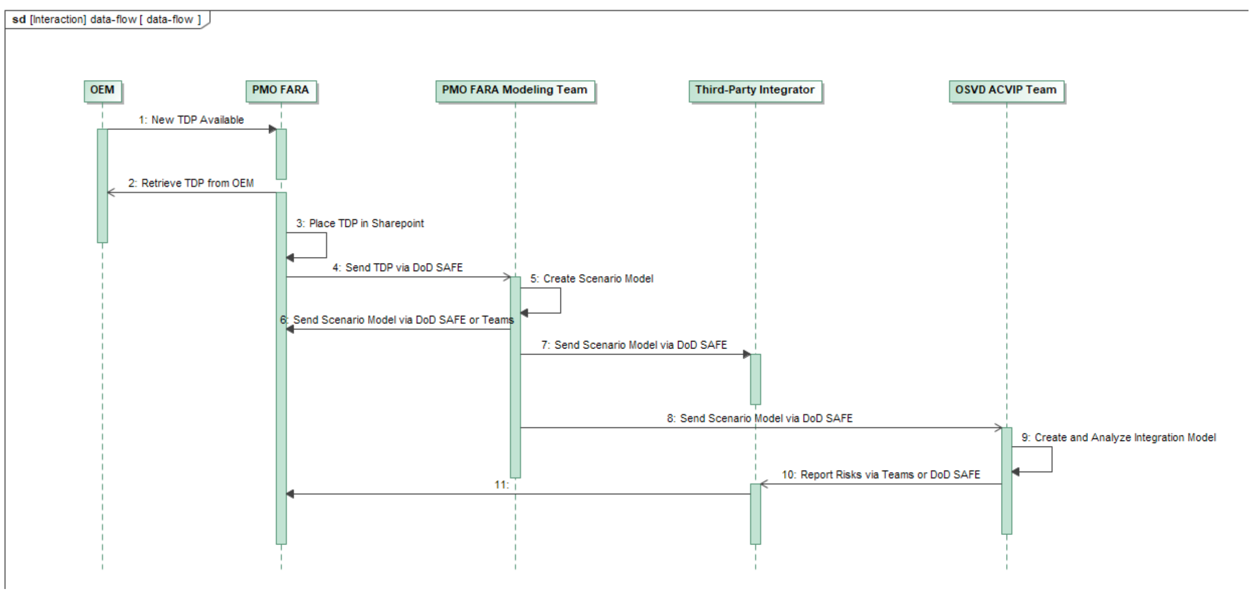


Figure 1 Data Transmission Steps Required for OSVD

We used DoD Secure Access File Exchange (SAFE) for most file transmission needs; however, DoD SAFE has some significant limitations:

- SAFE file transfers time out after a short period of time 1-7 days, so if a recipient misses a transmission, it must be resent.
- Only Common Access Card (CAC) holders can initiate SAFE transfers.
- Transferring SysML models via SAFE requires extracting the models from other version control systems (e.g., Cameo Teamwork Cloud), which can affect identifiers and relationships in the models.
- Version control is very difficult through SAFE, because version history managed by Cameo Teamwork Cloud is lost.

Despite these limitations, we were able to obtain the necessary information to achieve the technical goals of the ACVIP team. In the future, we recommend using digital engineering environments that streamline the exchange of digital artifacts between organizations, or better yet remove the need entirely (**Recommendation B - Infrastructure**).

Near the end of our support of OSVD we gained access to the PEO Aviation Enterprise Local Area Network (ELAN), which allowed us to use the FARA digital engineering environment (e.g., PMO FARA Teamwork Cloud). Given more time, we likely could have transitioned our OSVD activities to this environment and gained considerable efficiency. The process for gaining access to the environment was inefficient and took a significant amount of time. We have consistently observed this type of challenge in multiple U.S. Army efforts; *these access issues are the U.S. Army's biggest challenge with respect to establishing and leveraging a digital engineering environment* (**Challenge 3 - Enabling Environment**).

In future OSVD or OSVD-like activities, we recommend using a common digital engineering environment accessible to USG, support contractors, and performer contractors, or streamlining the process of collaborating between environments. Such an environment will enable stakeholders to take advantages of other technologies like DevSecOps and Continuous Virtual Integration technologies, which Galois is applying on other programs (**Recommendation B - Infrastructure).**

Model Management

The OSVD activity required using and maintaining models from several sources, all of which were updated multiple times throughout the course of the OSVD events. These models (primarily in Cameo SysML) had extensive relationships and dependencies. Although these dependencies were not circular, the sheer volume of modeled data made model management challenging.

The data involved in OSVD was a mix of Controlled Unclassified Information (CUI) and proprietary data. We used Galois's CUI management infrastructure, which provided Virtual Desktop Instances (VDIs) and secure storage for managing CUI data. Galois, SEI, and Jovian were able to handle proprietary data via established Non-Disclosure Agreements (NDAs) with the Army and Proprietary Information and Inventions Agreements (PIIAs) with the performer contractors (i.e., OEMs).

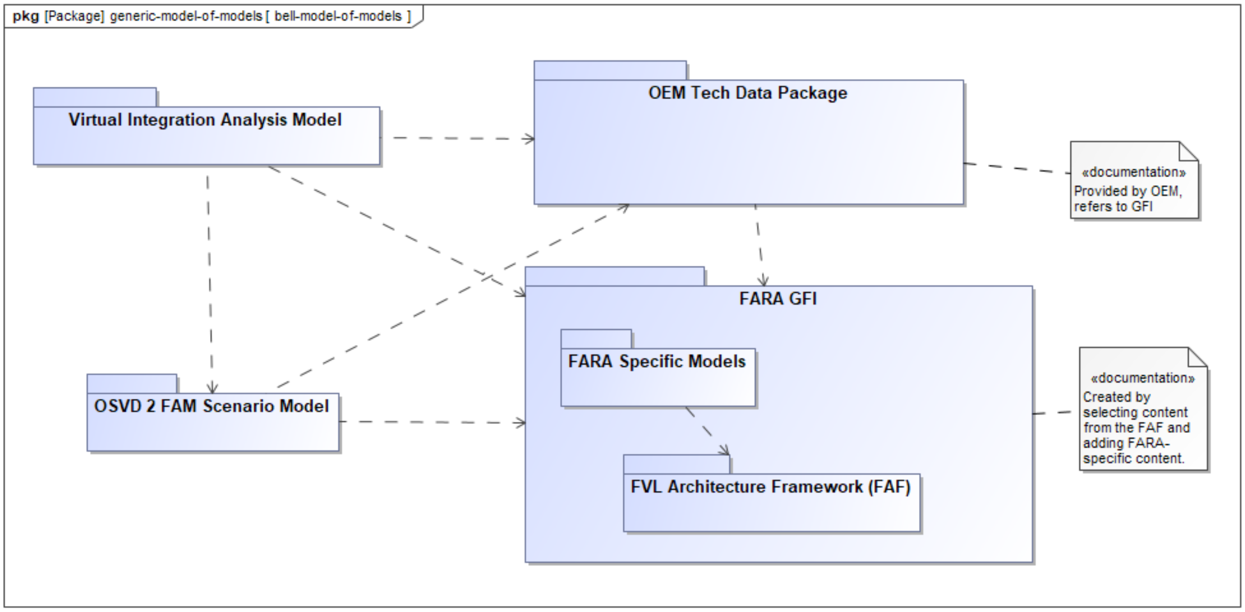


Figure 2 Model of Models for OSVD 2

During OSVD 1 we used Windows file shares (internal to Galois's CUI environment) to store common models that we needed to use but did not need to modify, such as versions of the FAF. We used an instance of Gitlab and multiple git repositories to store models (e.g., `mdzip` or `mdxml` files) that we needed to modify. This approach was viable but required manual version control and consistent file path management across the Galois team. This approach also required additional time because each team member had to copy content from file shares to his or her own working environment. This approach did not provide version control, so we had to use manual timestamping and versioning (e.g., by including a delivery date in the directory name for each TDP we received). This increased risk of confusion due to varying timestamps and version numbers (e.g., date Galois received delivery vs date performer provided) (**Challenge 2 - Inefficient Asset exchange**).

During OSVD 2 we assigned an engineer as a dedicated *model manager* and shifted all model storage to git repositories. This approach simplified our model management practices. We used separate repositories for each of:

1. Performer models (read only)
2. OSVD analysis models (read/write)
3. Shared model dependencies (GFI, scenario models, etc.) (read only)

We made the repositories containing performer models read only for all ACVIP team members except the model manager. Whenever we received updated performer models, GFI model, or scenario models, the model manager would update the repositories as needed and inform the rest of the team to pull changes. We found that this reduced confusion, ensured consistency among the team members and saved time compared to manual version management by filename/path. We recommend future projects using models from multiple organizations **designate a model manager** (**Recommendation B-Invest in accessible infrastructure**).

Cameo Teamwork Cloud

Cameo Teamwork Cloud (TWC) is a commonly recommended approach to managing models used by a team. We experienced problems installing and using Cameo TWC. As noted earlier, our workflow with other OSVD stakeholders (Performers, Government, and TPI) required exchange of models across organizational boundaries. Specific challenges and concerns were:

- The Linux version of TWC uses CentOS 7, which is at its end of life.
- The models used for OSVD were large, and we found that simply importing one of these models into TWC took over 10 hours, despite the host server clearly meeting all TWC system requirements.[5]
- Subsequent attempts to update TWC server models from updated local files failed after days of processing.

These limitations on digital engineering tools made it extremely inefficient to scale our workflows to keep pace with the size and scope of the Government and Performer-supplied models.

Syndeia and Teamwork Cloud

To reduce the engineering effort required to manage multiple revisions of models from various sources Galois acquired a license for Intercax Syndeia. Syndeia, also planned for use by PEO Aviation, offered potential capabilities for documenting and exploring digital threads across multiple digital artifacts. For example, in Galois's prior Army-funded study on Authoritative Source of Truth (ASoT) under the JMR MSAD Science & Technology (S&T) effort we demonstrated use of Syndeia to propagate changes to requirements from DOORS to SysML.

We experienced more challenges than expected setting up our environment to use Syndeia. The Syndeia documentation had multiple inaccuracies (e.g., incorrect path names) that made installation challenging. We encountered errors configuring authentication between Syndeia and our Cameo Teamwork Cloud (TWC) server. Although TWC is not a requirement of Syndeia many features of the web dashboard are only available when used in conjunction with TWC. Given more time we likely could have gotten Syndeia working, but the issues we encountered indicate an overall need for better scalability and robustness in model-management infrastructure.

Managing large models across multiple organizations incurred a variety of inefficiencies, and unfortunately, we were unable to successfully use Syndeia to overcome them. Direct access to a common digital engineering environment (e.g., the PEO Aviation ELAN) could likely remove some of those issues (e.g., by eliminating one or more organization-to-organization boundaries) (**Recommendation B-Invest in accessible infrastructure**). Absent the ability to directly access shared environments, we found that git was the most effective version control system for the scope and variety of data we used in OSVD.

[5] https://docs.nomagic.com/display/TWCloud2022xR2/System+requirements

Use of Models in Event Planning

In OSVD 1 the Government and TPI used PowerPoint diagrams to convey the scenario. **This was a mistake**. Use of PowerPoint required that the scenario planners ingest the Performer TDP and translate concepts from the TDP to a different medium, often using mixed nomenclature. Recipients of the scenario (e.g., the ACVIP team) had to ingest the PowerPoint scenario and translate that scenario back into the terminology of the Performer TDP. These two translation steps were unnecessary and introduced delay in collective understanding of the TDP. The Government addressed this issue by switching to SysML-based planning in OSVD 2.

OSVD Process Evaluation Q&A

Q. *How did having models help in understanding physical integration challenges?*
A. In OSVD, particularly in early events, the models were most helpful in determining system maturity and elements of the design that were high risk due to ambiguity or incomplete data.

Q. *How early in a program makes sense for virtual integration analysis?*
A. As we note above, we can identify potential risks even prior to virtual integration by reviewing ACVIP results provided by the performer as part of their baseline model. ACVIP can meaningfully identify gaps in a TDP early (e.g., at requirements time), but cannot identify specific likely integration errors until software and hardware have been defined and nominally allocated.

Q. *How much time is needed in virtual integration analysis to provide ample feedback to the integration team?*
A. The time required to perform virtual integration will generally exceed the time required to perform analysis of that virtual integration (i.e., once you've done the steps in *Table 4*, conducting analysis is a trivial matter of running tools). The time required to perform virtual integration will depend on the fidelity of the baseline model, the time to understand that baseline, and the complexity of the planned integration. This time may vary widely across different integrations. The time to conduct analysis, on the other hand, will remain mostly constant across different integrations because it mainly depends on the time to add necessary properties.

Q. *In Galois's experience were there particular model-based analyses more beneficial than others?*
A. The overall most useful analysis was data flow latency analysis. To analyze data flows that traverse large portions of the SUA architecture, an ACVIP analyst must investigate and correlate several aspects of the SUA architecture: its physical configuration, its network configuration, its software configuration, and its data items. *The presence or absence of this information and the degree of difficulty in correlating it into an analyzable form were strong indicators of the maturity of the SUA*—SUAs for which this information was missing or under-defined tended to experience more problems in the lab (i.e., discussed in section 6). Most of the issues experienced in the lab were due to software configuration or network configuration, so any virtual activities that reduce software and network risk are value-added.

Q. *How much time was needed to effectively conduct and report ACVIP findings?*

A. The ACVIP team needed approximately one to two engineering months of effort (i.e., 200 – 300 hours) over at least two calendar months to conduct ACVIP analysis and report findings for each OSVD event for each performer (see *Table 6* and *Table 7*). This time varied by the degree of change in the GFI, SUA, and TDP between subsequent events. The amount of time needed by the TPI to act on recommendations from the ACVIP team is not well defined, but the time available in OSVD 1 (several days) was clearly insufficient given lab results. Given the scope of information and familiarity we had, we recommend at least a month, ideally two, of calendar time for the TPI to accommodate ACVIP findings **(Recommendation C-Plan time for virtual activities**). We expect this time to decrease as teams gain familiarity with the associated artifacts and systems.

Q. *What types of information are needed for effective ACVIP analysis?*
A. Effective ACVIP analysis is analysis that reveals previously unknown risks. Effective ACVIP analysis for the types of activity conducted in this OSVD (i.e., reconfiguring existing hardware, software, and network) requires information on computing and networking hardware, software and its allocation to that hardware, network configuration, and data flows through the system. *Network configuration* arose as a key detail for which additional information would have reduced lab problems. Note that this OSVD did not have time-sensitive or security-sensitive requirements as part of the scenarios; if those had been included additional information would be necessary for effective analysis (e.g., time-space partitioning, security domains).

Q. *How do you maximize the benefits of ACVIP with respect to OSVD?*
A. ACVIP, and MBSE in general, should provide the *vernacular of planning and coordination*. Languages like SysML provide reusable and extensible artifacts that are critical in large-team coordination. For example, the Performers provided SysML models of their labs. When the TPI was able to use blocks from those SysML models (via *Used Project* relationships) the TPI was able to avoid communication errors that could otherwise manifest in planning (e.g., naming errors) and could trivially maintain parity with the Performer design since an update to the Performer TDP could be propagated to the OSVD Scenario or Analysis Models. The ACVIP team helped reduce risk simply by pressing the TPI to communicate in terms of the models (**Recommendation A-Use models for communicating**). Had the schedule been more accommodating to ACVIP analysis in OSVD 1, as it was in OSVD 2, ACVIP analysis could likely have contributed to more consistent lab results.

Q. *How do you maximize the benefits of ACVIP with respect to actual program?*
A. The more people using models to plan and coordinate, the better. Models can provide the lexicon needed for large and distributed teams to coordinate and collaborate (**Recommendation A-Use models for communicating**). ACVIP is an effective way to motivate content and elicit value from those models by motivating model fidelity and content. Decision makers must use models and model-based analysis to inform decisions, rather than making decisions and only using models to document those decisions.

Q. *What is the level of importance of having an ACVIP Plan/ACVIP Management Plan?*
A. The ACVIP Plan and contractor supplied ACVIP Management Plan are critical to the integration aspect of virtual integration, as they drive performer modeling activities and content (**Recommendation C-Plan time for virtual activities**). The ACVIP team used existing ACVIP

models and results which were motivated and governed by the FARA ACVIP Plan. The ACVIP Management Plan set forth the action plan for specific analyses for the ACVIP team and was necessary for effective coordination and execution of the ACVIP role. For example, during OSVD 1 the ACVIP team was segmented between the two performers and used the OSVD ACVIP Management Plan as a point of coordination between our segmented sub-teams.

Q. *What analysis should be performed by the PM and what should be reviewable/understood by the PM?*
A. This is a difficult question to answer without a specific scenario. In general, the OEM should provide evidence or artifacts from all analyses related to architectural components (per the FAF, architectural components are those that are modular) and the PM should review and understand all analyses related to architectural components. For example, if an end-to-end data flow traverses one or more architectural (modular) components, the PM should be able to review and understand the latency analysis of that flow. If the OEM provides a digital engineering environment, that environment should enable the PM to trivially replicate any analyses related to architectural components. Performing analysis for the sake of review is in the scope of the PM. Performing analysis for the sake of design decisions is largely in the scope of the OEM.

6. Critical Program Events and Outcomes

This section enumerates our specific activities and contributions chronologically and correlates them with the findings and recommendations we provide earlier in this report.

OSVD ACVIP Artifacts

We provided the following artifacts to PMO FARA from our support of OSVD (Table 5). Note that this table includes deliverables from both W911W6-22-F-703C (DO11) and W911-W6-23-F-703A (DO12).

Table 5 OSVD ACVIP Artifacts

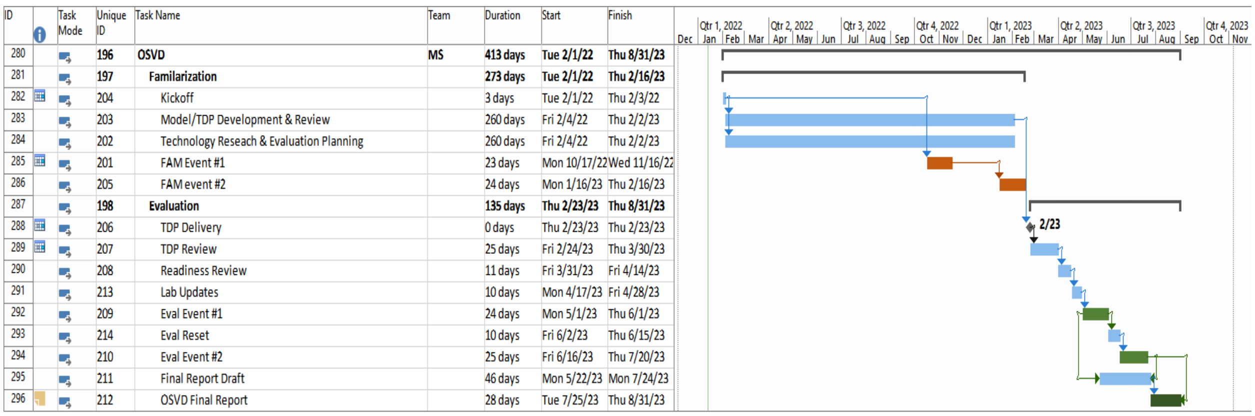
CDRL	Name	Description	Notes
DO11 A004	ACVIP Management Plan (AMP)	A plan describing our modeling and analysis approach for OSVD.	
DO11 A004	Sikorsky ACVIP OSVD 1 Fam1 Report	ACVIP team findings for OSVD 1, Familiarization Event 1 for Sikorsky.	We did not have sufficient time to conduct modeling for the Fam1 event.
DO11 A004	Bell ACVIP OSVD 1 Fam1 Report	ACVIP team findings for OSVD 1, Familiarization Event 1 for Bell.	We did not have sufficient time to conduct modeling for the Fam1 event.

CDRL	Name	Description	Notes
DO11 A004	Sikorsky ACVIP Fam2 Report	ACVIP team findings for OSVD 1, Familiarization Event 2 for Sikorsky.	
DO11 A004	Bell ACVIP OSVD1 Fam2 Report	ACVIP team findings for OSVD 1, Familiarization Event 2 for Bell.	
DO11 A004	Sikorsky ACVIP OSVD 1 Eval1 Report		
DO11 A003	Sikorsky ACVIP OSVD 1 Eval1 Models		
DO11 A004	Bell ACVIP OSVD 1Eval1 Report		
DO11 A003	Bell ACVIP OSVD1 Eval1 Models		
DO12 A003	Sikorsky ACVIP OSVD1 Eval2 Report		
DO12 A005	Sikorsky ACVIP OSVD 1 Eval2 Models		
DO12 A003	Bell ACVIP OSVD 1 Eval2 Report		
DO12 A003	Bell ACVIP OSVD 1 Eval 2 Models		
DO12 A003	Sikorsky OSVD 1 Overview	A summary of ACVIP team findings from OSVD 1 for Sikorsky	
DO12 A003	Bell OSVD 1 Overview	A summary of ACVIP team findings from OSVD 1 for Bell	
DO12 A003	Sikorsky OSVD 2 Monthly ACVIP Reports		Delivered in January and February, 2024
DO12 A005	Sikorsky OSVD 2 Monthly ACVIP Models		Delivered in January and February, 2024
DO12 A003	Bell OSVD 2 Monthly ACVIP Reports		Delivered in January and February, 2024

CDRL	Name	Description	Notes
DO12 A005	Bell OSVD 2 Monthly ACVIP Models		Delivered in January and February, 2024
DO12 A004	Final Report	This Report	

OSVD 1

OSVD 1 had an aggressive schedule that provided only a couple of months between events (note that each event listed in Figure 3 included two lab events, one for each performer). The TDP deliveries did not perfectly follow the schedule, and the ACVIP team was often waiting for a TDP update.



ID	Task Mode	Unique ID	Task Name	Team	Duration	Start	Finish
280		196	**OSVD**	MS	**413 days**	**Tue 2/1/22**	**Thu 8/31/23**
281		197	**Familarization**		**273 days**	**Tue 2/1/22**	**Thu 2/16/23**
282		204	Kickoff		3 days	Tue 2/1/22	Thu 2/3/22
283		203	Model/TDP Development & Review		260 days	Fri 2/4/22	Thu 2/2/23
284		202	Technology Reseach & Evaluation Planning		260 days	Fri 2/4/22	Thu 2/2/23
285		201	FAM Event #1		23 days	Mon 10/17/22	Wed 11/16/22
286		205	FAM event #2		24 days	Mon 1/16/23	Thu 2/16/23
287		198	**Evaluation**		**135 days**	**Thu 2/23/23**	**Thu 8/31/23**
288		206	TDP Delivery		0 days	Thu 2/23/23	Thu 2/23/23
289		207	TDP Review		25 days	Fri 2/24/23	Thu 3/30/23
290		208	Readiness Review		11 days	Fri 3/31/23	Fri 4/14/23
291		213	Lab Updates		10 days	Mon 4/17/23	Fri 4/28/23
292		209	Eval Event #1		24 days	Mon 5/1/23	Thu 6/1/23
293		214	Eval Reset		10 days	Fri 6/2/23	Thu 6/15/23
294		210	Eval Event #2		25 days	Fri 6/16/23	Thu 7/20/23
295		211	Final Report Draft		46 days	Mon 5/22/23	Mon 7/24/23
296		212	OSVD Final Report		28 days	Tue 7/25/23	Thu 8/31/23

Figure 3 OSVD 1 Schedule

The ACVIP team (consisting of CMU SEI and Galois) was actively involved in all eight OSVD 1 events and actively participated in six of the eight OSVD 1 events (Familiarization Event 2, Evaluation Event 1, and Evaluation Event 2 for each performer). The ACVIP team performed model-based dry runs of each event integration scenario and provided input to the TPI team regarding anticipated problem areas or challenges identified by ACVIP analysis. Several risk areas identified by ACVIP assessment emerged as pain points in the lab activities, validating the ACVIP assessment.

The most significant challenge we encountered in OSVD 1 was the availability of design artifacts and integration plans. The ACVIP team was limited by the time available between the determination of each OSVD 1 event scenario and the lab event, and in practice was only able to provide risk recommendations to the TPI *a few days before the lab event* (**Recommendation C-Plan time for virtual activities**).

Another challenge we encountered was the use of PowerPoint-based design artifacts to communicate the integration scenarios. Such artifacts were insufficiently detailed to provide clear direction. For example, for the one Performer the presence or absence of critical component in the lab for OSVD 1 Fam 2 was ambiguous in the model. In these activities that involved reconfiguring the SUA network, we found that by observing where there was ambiguity in the integration plan, problems arose in practice (**Challenge 1-Ambiguity in design artifacts**). For example, in the one TDP we noted that the allocation of software to hardware was undefined. In OSVD 1 Eval 2 some data flows were under-defined. These ambiguities led to delays in the lab, as described in the lab outcomes below.

Tabletop Event

In May 2022 we participated in a "tabletop" planning event in Huntsville in which we discussed various stakeholder roles and workflows through the OSVD events. This activity was effective for clarifying the objectives and workflow of OSVD. Unfortunately, contractual issues made it difficult to execute the planned workflow, as the CMU SEI team had to pause their involvement partway through OSVD 1 due to waiting on award and funding. Regardless, we recommend such activities for future OSVD or similar collaborative efforts with multiple distributed stakeholder organizations (**Recommendation C-Plan time for virtual activities**).

Familiarization Event 1

Date: October-November 2022

Description: Familiarization event 1 (Fam 1) centered around integration of the Crew Mission System (CMS) in the performer SUAs. CMS was an existing technology well known to the TPI and thus presented little risk for integration.

Findings: The ACVIP team did not have sufficient design artifacts and details on the plan for Fam 1 in time to ingest and apply the performer models and models of the CMS. Due to this limitation, we did not conduct virtual integration analyses, and instead conducted a review of the TDP and provided feedback to the Government based on our review (see Table 5).

Familiarization Event 2

Dates:

- ACVIP Assessment: December 2022 – January 2023
- Lab Activity: January – February 2023

Description: Familiarization Event 2 (Fam 2) focused on replacement of components of the SUA with components (hardware and software) provided by the TPI.

Findings: ACVIP evaluation suggested risks regarding configuration of the software and data flow in one SUA and insufficient information to suggest risks for another SUA. Configuration errors for the Transport Service Segment (TSS) manifested in the lab.

Evaluation Event 1

Date: May 2023

Description:

Eval 1 called for the TPI to add a new tactical radio with situational awareness information to the SUA. This scenario required configuration of port and network infrastructure in the performer environment. Note that the planning for these events was largely conducted via PowerPoint.

ACVIP analysis suggested risks in the area of network configuration and processing capacity. Lab results provided by the TPI indicate that the ambiguity in the a SUA manifest in difficulty configuring the Transport Service Segment (TSS) in the lab. However, the processing capacity risk identified did not manifest in the lab. *The TPI reported software and network configuration issues as the main challenges.*

Table 6 OSVD 1 Eval 1 ACVIP Effort

Performer	ACVIP Expected Effort (Hours)	ACVIP Actual Effort (Hours)
Bell	REDACTED	
Sikorsky		
	486	530

Evaluation Event 2

Date: Jul/Aug 2023

Description:
Evaluation Event 2 called for the TPI to add a notional “Quantum EGI” to the SUA. This addition required several modifications to the SUA, including updates to its network configuration and addition of new hardware.

ACVIP Analysis of the a TDP suggested risks in network configuration and in the behavior of the quantum EGI. *Both of these risks manifest in the lab as significant pain points*. ACVIP analysis of a TDP suggested performance impacts due to extended data flows and processor utilization.

For the TPI was able to collect timing measurements in the lab, which enabled us to compare and contrast predicted latency measures against lab measurements. Unfortunately, software problems in the QEGI added significant latency and largely masked relevant results from the change to the SUA.

Table 7 OSVD 1 Eval 2 ACVIP Effort

Performer	ACVIP Expected Effort (Hours)	ACVIP Actual Effort (Hours)
Bell	REDACTED	
Sikorsky		
	486	494.5

OSVD 2

The FARA program was cancelled in February, 2024, two months before the OSVD 2 familiarization event was scheduled to take place. However, the scenario was defined sufficiently early enough for the ACVIP team to evaluate the performer TDPs and provide input and models to the TPI and the Government.

Familiarization Event 1

Date: 2024

Description: For OSVD 2 the Government provided a model-based scenario. The scenario model provided by the Program Management Office for the Future Attack Reconnaissance Aircraft (PMO FARA) included physical connections between the Mission Data Recorder (MDR) and the performer system. The scenario model also included the Future Airborne Capability Environment (FACE™) Standard software component integration details describing the connections between the performer system and the MDR FACE Portable Component Segment (PCS) layer software component. The model-based scenario made it significantly easier to resolve ambiguities in the scenario because scenario used the Performer TDP as its lexicon and the SysML semantics enforced more consistent naming, associations, and traceability to common component definitions.

7. MBSE Ecosystem Contributions

ACWG

In addition to supporting the OSVD, Galois supported several Army Aviation MBSE efforts related to ACVIP and Digital Engineering. We supported the PEO Aviation Architecture Collaboration Working Group (ACWG). We have been regular contributors and attendees of the ACVIP Subgroup, Digital Engineering (DE) Subgroup, and Airworthiness Subgroup. Mr. Smith served as the co-chair of the DE Subgroup and helped facilitate a series of panel discussions around best practices and challenges for digital engineering. The output report from that activity is included in Appendix B.

Galois is the creator of several packages in the FAF, including the AADL profiles and the ACVIP workflow models, the majority of which we created on prior task order W911W620F703A / W911W620F703A (DO09). Only minor changes to these profiles were required during the period of this project.

FARA

We collaborated regularly with FARA staff on a variety of topics, including ACVIP, DE, and MBSE. We participated in several FARA working groups, including the FARA DE, MBSE, and ACVIP Working Group, a FARA Performer Modeling and Simulation Accreditation Working group, FARA Performer OSVD, ACVIP, and MBSE Status Meetings, and the FARA Prognostics Verification Validation and Accreditation (VV&A) group. These groups helped inform our activities in support of OSVD. In many cases, such as the FARA DE, MBSE, and ACVIP working group, we made significant contributions to the strategy and direction of the group. For example, we leveraged our experience from the JMR MSAD ASoT study to help in the refinement of the FARA digital engineering approach (Smith, et al., 2021).

8. ACVIP Tools Contributions

Galois (then Adventium Labs) created the Curated Access to Model-based Engineering Tools (CAMET) Library in 2018 to facilitate transition of research and development technology to Government and industry stakeholders.[6] We had created a variety of analysis tools (such as the FASTAR timing analysis tool) and needed a sustainable mechanism to provide these tools to end users, receive user feedback, and manage user access (Figure 4). With input and feedback from Government stakeholders including Army DEVCOM, we decided to create CAMET as that mechanism. CAMET is a web-portal (https://camet-library.com/camet-tools) for providing MBSE tool access to Government and Industry users and for commercializing such tools for long term sustainability. We successfully employed CAMET to provide tools to participants in the JMR MSAD Capstone Exercise.

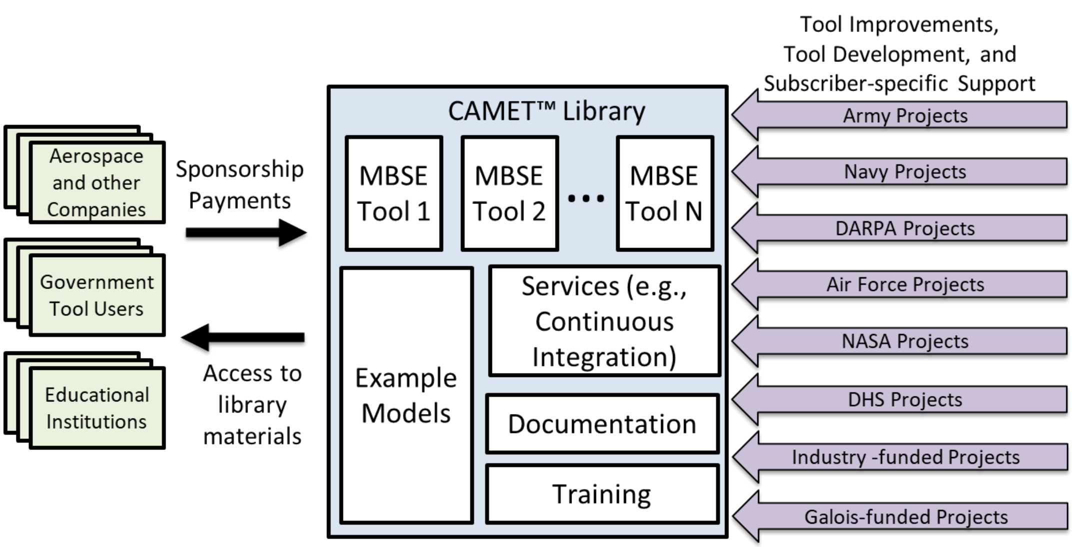


Figure 4 CAMET Structure - Government R&D efforts generate MBSE tools available to Government and industry.

Based on feedback from FARA leadership and interest from industry, in 2021 and 2022 we defined a plan to scale CAMET for enterprise use and put it on a pathway to sustained success. This plan included creation of an enterprise tier of CAMET subscription to include software maintenance and support. METAL-V DO12 (W911W6-17-D-0003 W911W623F703A) included an Enterprise CAMET subscription for the FARA program. As part of the FARA program's

[6] https://camet-library.com/

enterprise subscription we collaborated with PEO Aviation G6 to make CAMET tools available to FARA staff.

We provided several updates to CAMET tools on this project, such as an update to the SysML to AADL Bridge that provided bi-directional generation capability between SysML and AADL.

In 2024, based on feedback from FARA stakeholders, Galois removed the previously agreed to user limitation on U.S. Government access to CAMET, which now means that all U.S. Government staff have unlimited access to download and use CAMET tools.[7] We provided formal documentation of this update in a separate deliverable.

Despite the cancellation of FARA, CAMET commercialization has continued to grow and our engagement with stakeholders across the DoD around CAMET and ACVIP has continued to increase. In our engagement with stakeholders around the DoD, we regularly hear acknowledgements of the Army's pathfinding in digital engineering. The ACVIP process and tooling investment from the Army, including FARA and FLRAA, has made a significant impact in its adoption.

MBSE Ecosystem Q&A

Q. *What needs to be understood with the continuous/recurrent engineering costs of tool updates with respect to standards updates and error corrections and improvement in tools?*
A. Standards updates and tool maintenance are likely to accelerate, not slow down. The ACVIP and MBSE community should produce more tutorial-type content (particularly videos) to help new users with evolving tools and standards. The DoD needs to invest in tools and tools support and expect a recurring cost to maintaining ACVIP and MBSE capabilities.

Q. *Were any issues seen with dealing with OSATE?*
A. We did not experience any significant issues with OSATE.

Q. *Were any issues seen dealing with CAMET?*
A. We experienced some challenges with the CAMET FASTAR timing analysis tool because it expects hardware binding details that were not always available in the performer models.

Q. *Were any issues seen with dealing with the SysML ←→ AADL translator?*
A. Yes, we discovered and fixed several minor issues with the translator. We also received feedback from the FARA performers.

Q. *Were any issues seen dealing with the FACE → AADL translator?*
A. Yes, we discovered a problem with FACE integration models that incorporate elements from several namespaces. Galois collaborated with CMU SEI to determine a fix for this issue, which CMU SEI applied on 15 February, 2024.[8] A performer reported on 2 May 2024 that the corrections made by CMU SEI works.

[7] Tool maintenance and user support is available for a fee.
[8] https://github.com/osate/face2aadl/pull/8

Q. *Why should an organization use CAMET Enterprise support? When is it needed by organization versus just tool access?*
A. CAMET Enterprise support provides custom tool enhancements and priority bug fixes. For example, PEO Aviation G6 requested a single .zip install of the CAMET Base Pack to simplify their installation process. As part of the FARA PM's CAMET Enterprise support, we provided that capability. Similarly, a CAMET Enterprise provides guarantees of updates to CAMET tools for new versions of OSATE, MagicDraw, Cameo, etc.

Q. *How does an organization and individuals in the Government obtain access to download the CAMET tools?*
A. Base CAMET access is free for the U.S. Government and available for a fee to industry. Request access by emailing camet-library@galois.com or visit camet-library.com.

Q. *What lessons learned and recommendations did the FARA performers have with regards to tools that need to be highlighted?*
A. The two most significant themes in user reports were: (1) simplify installation of MBSE tools and (2) support a variety of modeling paradigms. MBSE tool adoption in industry is heavily dependent on tools fitting together in a cohesive workflow and fitting into existing information technology infrastructure.

9. ACVIP Process Contributions and Recommendations

The application of the Architecture Centric Virtual Integration Process (ACVIP) normally follows a standard path for performer contractors. First, the PM defines an ACVIP Plan that enumerates the integration risks that ACVIP should expose and the analyses that performers should conduct to expose those risks. The ACVIP Plan calls out specific analysis goals without mandating particular analysis tools to achieve those goals. Next, the performer responds to the ACVIP Plan with an ACVIP Management Plan that enumerates the specific analyses the performer will conduct to achieve each goal, the frequency to conduct those analyses, the tools to conduct those analyses, and the intended presentation of the analysis results. Finally, the PM evaluates the performer's ability to execute an approved ACVIP Management Plan.

The OSVD activity shifted the focus of ACVIP from the performers themselves to a TPI acting in the role of a Mission System Integrator (MSI). The TPI would take a base system provided by each FARA performer and attempt to integrate new components chosen by PM FARA. Prior to physical integration, the PM FARA directed a separate team, the ACVIP team comprising Galois (lead) and CMU SEI, to conduct virtual integration and analysis using performer-provided TDP and to identify potential risks that the TPI might encounter during physical integration. The application of ACVIP for the OSVD activity thus had two parts: (1) attempt to conduct virtual integration using a model of the performer's base system, as found in the TDP, and models of the new components in order to identify potential integration risks, and (2) conduct ACVIP on the integrated models in order to identify potential integration impacts. The first part would expose gaps in the performer's TDP to support virtual integration. The second part would expose ways in which the integrated system might violate safety, security, and performance requirements.

The OSVD activity differed from a typical performer-centered development in two important ways. First, the FARA ACVIP Plan was still in development as the performers prepared their TDPs. Although the performers were aware of typical analysis goals, there did not yet exist a PM FARA mandate to deliver a TDP containing models that support any specific analysis goals. Instead, the performers could support analyses of their own choosing. (The ACVIP team crafted an ACVIP Management Plan specific to the OSVD activity that called out specific analyses that the ACVIP team itself would attempt to conduct.) Second, the ACVIP team did not have direct contact with the performers, so the ACVIP team had to rely exclusively on the performer's TDP to provide necessary analysis support. As a result, the ACVIP team could not easily conduct analyses beyond those already supported by the performer.

The ACVIP-focused virtual integration provided a unique benefit to the MSI. During the physical integration, the TPI demonstrated basic functionality for the integrated components, but the MSI did not conduct extensive system testing to assess the safety, security, and performance impacts of that integration. The ACVIP team, on the other hand, was able to extend performer-provided ACVIP analyses and demonstrate, through those analysis results, those potential impacts. An example of this benefit occurred during OSVD1, when the ACVIP team was able to demonstrate the latency impact of the MSI's QEGI integration approach.

During execution of the OSVD activity, the ACVIP team discovered that the performer's own ACVIP analysis results provided important hints about potential integration impacts that the TPI should consider. For example, a performer TDP's ACVIP results called out already fully utilized processor partitions that the MSI should avoid extending with new software during physical integration. *We recommend that the TPI carefully review these performer-provided ACVIP results as part of integration planning (**Recommendation C-Plan time for virtual activities**).*

The ACVIP team followed a standard process during the virtual integration activities for OSVD. First, using the TPI's integration plan, the ACVIP team attempted to virtually integrate the new components. In doing so, the ACVIP team identified areas of the integration plan that the performer TDP was not intended to support, and the team identified challenges that the TDP posed to virtual integration. For example, hand modifying generated AADL generated from a different model means that updating the specifications to include any new components would require a similar translation process, which could be a challenging task for an TPI.

Second, following virtual integration, the ACVIP team extended performer-provided ACVIP analyses to include the new components.

ACVIP Process Q&A

Q. *Based on this OSVD, would you update the recommendations for types of analysis to be performed at the respective lifecycle milestones?*
A. We recommend evaluating the availability of information for all analyses as easily as possible. Even if the results of the analysis are incorrect or incomplete, the ability, or lack thereof, of a TDP to support analysis can indicate where ambiguities in the design may introduce or indicate risk.

Q. *Are there recommendations in ACVIP handbooks that should be updated based on how OSVD executed?*
A. The ACVIP handbooks should be updated to describe the transition between high level modeling languages (e.g., SysML) and lower-level languages (e.g., AADL). The handbooks should also be updated to place extra emphasis on analyzability early (e.g., by recommending that ACVIP practitioners use notional or best guess values in their models to facilitate analysis).

Q. *What are the recommended types of information needed in MBSE models to run ACVIP analysis?*
A. Based on the challenges observed in this OSVD, additional information and additional analysis tools should be provided and/or created to support network configuration analysis. In this OSVD network configuration details were often spread across two or more different artifacts, making them difficult to understand and analyze.

Q. *How should ACVIP teams work with the MBSE SE teams? How integrated do the ACVIP analysis folks need to be? Was it difficult being external vs working more internally on the PM teams?*
A. The ACVIP team and MBSE team should be one and the same – ACVIP should simply be a tool in the MBSE toolbox (**Recommendation D-Train into culture change**). The ACVIP team being external added communication delay and made it more difficult for the ACVIP results to factor into scenario planning.

10. ACVIP Training Contributions and Recommendations

As part of our overall support for the FARA program Galois conducted an ACVIP training course for Army Aviation staff in 2023. In the four-day course we had a maximum of 27 attendees and an average of 22.25 students/day. We tailored the content of our standard ACVIP course to focus on FARA in general and OSVD in particular, using the Performer TDPs where possible in course activities. We found that many attendees were insufficiently prepared to use the tools and technologies required for ACVIP; most students lacked proficiency in SysML tools. We provided a lesson learned summary to the Government describing these findings in more detail.

Based on the outcomes of that training, we met with FARA stakeholders to help develop a broader training plan for Army Aviation engineering staff. Figure 5 shows skill dependencies necessary to conduct ACVIP analysis for FARA. To effectively conduct ACVIP for FARA, practitioners need proficiency in the FARA GFI, FAF, MBSE, and ACVIP. Most attendees in our training course lacked some or all these skills. For future efforts, we recommend developing a training program that breaks down key outcomes (e.g., identify risks through ACVIP virtual integration analysis) into prerequisite skills tailored to the program and job role (**Recommendation D-Train into culture change**). For example, a mission system software reviewer would likely need proficiency in everything in Figure 5 except for HOST. Specific job functions or analyses (e.g., cybersecurity or airworthiness) would require additional tailoring of this list. For example, Risk Management Framework (RMF) analysis review would require additional training in RMF and likely in model-based RMF analysis tools.

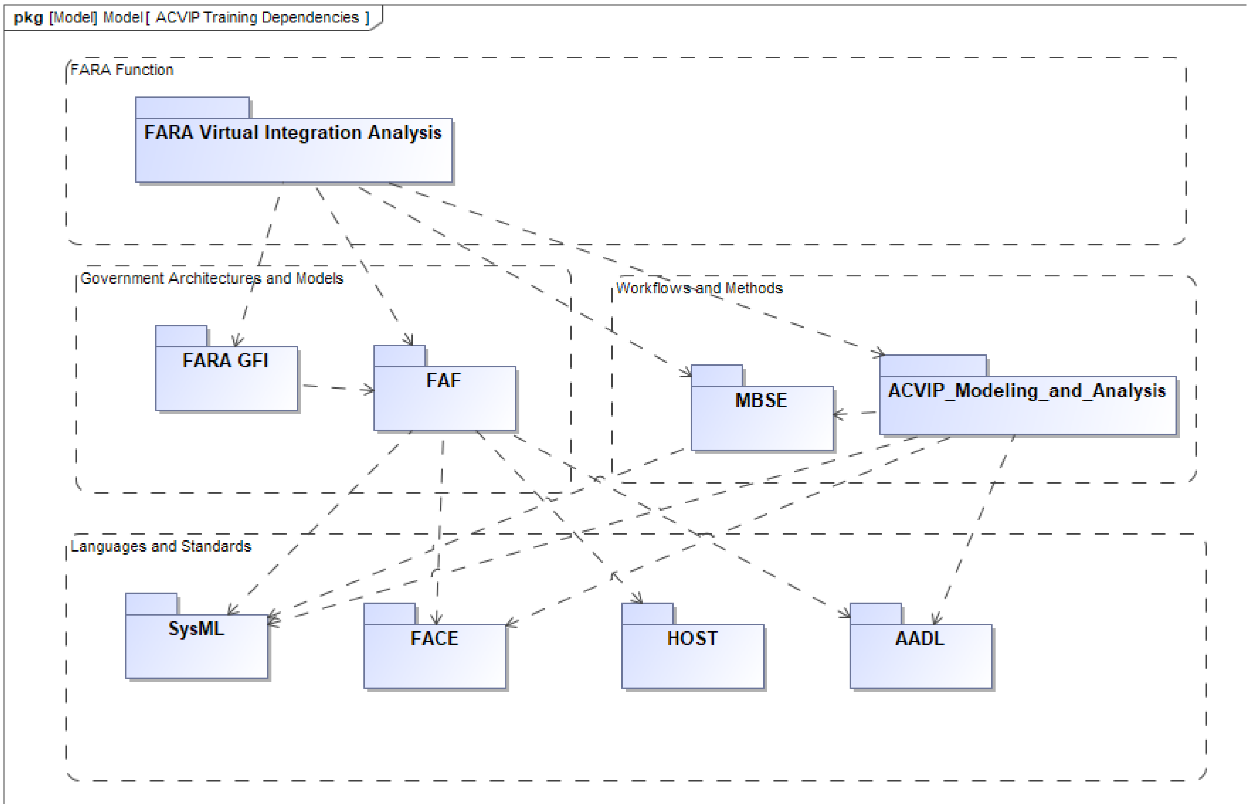


Figure 5 Training Dependency Diagram. The elements on the bottom are prerequisites to the items above them.

ACVIP Training Q&A

Q. *What is the recommended sequence of classes needed to achieve depth of knowledge to create and execute model-based analysis regarding MBSE? ACVIP?*

A. All technical staff should be trained in SysML sufficient to interpret and act on common SysML diagrams (e.g., workflow diagrams). Building on that training, most technical staff should be trained in MBSE practices to create such diagrams. Building further, technical staff who have responsibilities for elements of cyber-physical systems, specifically at the boundary between software and hardware, should be trained on ACVIP (see Figure 6).

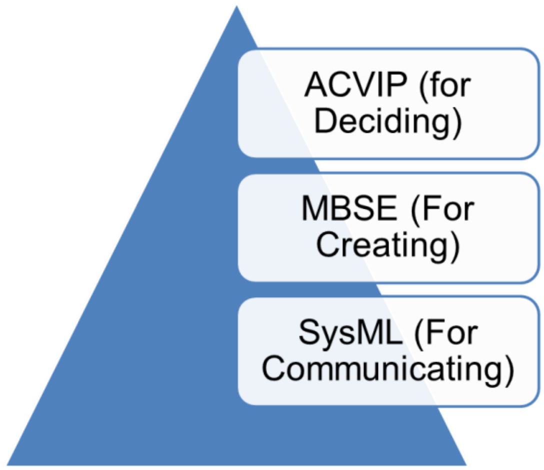


Figure 6 ACVIP Skills Hierarchy

Q. Are there different course paths to take depending on what type of stakeholder you are training (e.g., airworthiness, cybersecurity, PM Technical, test, PM Management)?
A. The core skills and training are the same for all the listed categories – we recommend at least 16 hours of training each of SysML, MBSE, AADL, and ACVIP and in that order. For specific types of analysis (e.g., safety analysis) the Army should require additional training.

11. Recommendations for Future OSVDs

Clearer Functional Objectives: The scenarios for OSVD 1 were necessarily simple to allow rapid integration. However, such scenarios are not representative of the ideal rapid reconfiguration capability. Future OSVDs should aim to change components without negative impact to functional capability. For example, in OSVD 1 Eval 2 the TPI added a Quantum EGI which negatively impacted latency. Because specific latency requirements were not part of the evaluation, flexible approaches to configuration (such as best-effort networking) were acceptable. Future OSVDs, particularly those dealing with more mature systems, should be stricter.

Model-Based Planning: For future OSVDs we recommend model-based scenario planning, as was implemented in OSVD 2. Model-based planning helps avoid terminology confusion, duplicative documentation, and ambiguous artifacts (**Recommendation A-Use models for communicating**).

Emphasis on Network and Software: Problems with network configuration and software configuration were a common theme in this OSVD. We recommended increased emphasis on these information items in the scenario planning, performer design and system architecture artifacts, and analysis approach (**Recommendation A-Use models for communicating**).

Improved Digital Engineering Environment: Many of the collaborators were required to use DoD SAFE to exchange information, which added friction and delay to already tight integration and lab schedules. A digital engineering environment with role-based access control would alleviate many of those issues (**Recommendation B-Invest in accessible infrastructure).**

12. Recommendations for Future Research

Artificial Intelligence and Machine Learning in Airworthiness Assessment

The growing interest and use of Machine Learning (ML) and Artificial Intelligence (AI) provides novel challenges in airworthiness assessments. Of particular concern are the implications and process for evaluation and certification of ML and AI algorithms across a range of use cases. We see three broad topics in future research: (1) algorithm and training data evaluation, (2) closed-loop evaluation, and (3) acquisition requirements.

Algorithm and Training Data Evaluation: ML and AI algorithms are entirely dependent on the data on which they were trained. Furthermore, for most, if not all use cases, such models will be used in scenarios outside of the training data, making evaluation of all data-related aspects from understanding the training data to evaluating model performance within and outside of the region of training and evaluation data critical. Take, for example, an algorithm trained to predict aircraft maintenance needs. While operating conditions are perhaps the largest contributor to aircraft maintenance needs, due to the extreme variability in aircraft operating domains and flight histories, it is almost guaranteed that the predictive algorithm will be predicting on previously unseen scenarios. To determine how much to trust the model in each novel scenario, it is necessary to determine how close that scenario is to the training data, as well as model performance and sensitivity in that space. To do so, we need methods for determining which scenarios were covered in the training data (classically called the *domain of validity* of a model), and the dimensions which contribute the most to model reliability (*model sensitivity*).

The domain of validity for a data-driven model can be computed as the space encompassing all the training data for a model. Thus, if you want a model to perform well in high and low temperature settings, you should ensure training data covers a broad range of temperatures. However, for models that attempt to predict complex interactions over time, with interdependent variables, such as those which would be employed for predictive maintenance, simply training data points relative to variables of interest is insufficient. Input data may have hidden causal relationships between variables which influence model performance and bring unaccounted for biases into predictions. For example, a model may have been trained on data where missions flown during the warmer daytime hours were less damaging to an aircraft than those flown during cooler nighttime hours. A model trained on this data may correctly identify the correlation between temperature and aircraft damage, leading to high prediction accuracy (e.g., determining that aircraft flown mainly at night required maintenance sooner). However, it is highly likely that a data-driven model incorrectly attributes a causal relationship to this correlation (i.e., higher temperature results in reduced damage), when in actuality differences in damage were due to the types of missions flown, not temperature (Kushner, Sankaranarayanan, & Breton, 2020). For such a model, the domain of validity should not be classified as “all temperatures” but rather “all temperatures, given that type A missions are flown at higher temperatures while type B missions are flown at lower temperatures.”

Model sensitivity refers to how much model output changes based on changes in model input. For example, if we continue our predictive maintenance task, a model may dramatically change predicted time of repair for an engine as the length of missions flown increases. One particularly beneficial feature of determining model sensitivity is that it enables “grounding” of model performance relative to known “ground truth” requirements such as “flying through sandstorms increases aircraft wear.” Research in this space would improve our understanding of the relationship between data and models, and help inform acquisition requirements, defined below.

It is also important on applying AI/ML to maintenance data (like Health and Usage Monitoring Systems (HUMS)) that the algorithms are trustable especially if one is going to use for extending scheduled change out of parts as with Condition Based Maintenance (AMRDEC, 2016).

Closed-Loop Evaluation: In addition to understanding training data and model performance across different use cases, it is necessary to determine how to evaluate ML and AI components when they are a part of a larger system, such as an ML/AI based predictive model inside of an autonomous aircraft vision system. For cyber-physical systems, we are typically concerned with the question of whether for *all possible environment scenarios*, does the closed-loop system exhibit the desired behavior (e.g., do desired properties hold?) On a practical level, these properties often characterize safe vs unsafe behaviors. Due to the infinite scenarios a CPS system can encounter during deployment, testing scenarios individually is insufficient. Instead, formal methods based on bounded-time reachability analysis, simulation-guided reachability analysis, deductive techniques based on safety invariants, and formal, requirement-driven testing techniques can better characterize and evaluate CPS performance. This closed-loop evaluation would enable robust analysis of ML/AI based systems as they would be deployed and could help identify complex errors such as those occurring due to interactions of software-hardware-environment interactions on the system and subsystem levels.

Acquisition Requirements: To effectively evaluate ML and AI algorithms, and systems with these algorithms as components, the criteria for documentation and what must be delivered alongside the algorithms should be determined. Based on our work with the Army Systems Readiness Directorate (SRD), this is a topic which is currently in progress but for which standards have not yet been determined. We believe the most effective way to determine what should be asked for alongside these algorithms is to determine how these models will be evaluated and determine a minimum viable set of materials needed to ensure that evaluation is possible. This includes considerations about how data should be documented and delivered, model evaluation results, and more. To relieve undue burden on reviewers, we anticipate a single set of criteria, regardless of use case, with evaluation adjusting based on the safety criticality of the component with which ML or AI is involved. The Army should invest in future research to define and validate these criteria.

SysMLv2 Transition

In the OSVD activities, SysMLv1 proved to be a viable modeling language for specifying GFI, conveying OEM design, communicating integration scenarios, and facilitating ACVIP analyses.

However, the Cameo ecosystem produced several friction sources that slowed progress or limited capabilities:

- **Teamwork Cloud Import/Export:** Sharing models between organizations required exporting and importing models from and to different instances of Cameo Teamwork Cloud. Each such export/import operation could take hours.
- **Identifier Changes:** Exporting from Teamwork Cloud can affect the identifiers of SysML elements, making version control of large models difficult.
- **Complex Toolchain:** Most ACVIP analysis tools run on AADL models, and as such require translation from SysML to AADL. Although the CAMET toolset enables this translation, the process nevertheless adds a time and training burden on users.
- **Vendor Lock:** The Army selected Cameo Enterprise Architect for SysML editing. As Cameo uses a proprietary model format, this effectively forced the performers and TPI to use Cameo as well.

SysML version 2 (SysMLv2) aims to address many of these needs. The Application Programming Interface (API) planned for SysMLv2 may streamline access across organizations. SysMLv2's textual format may reduce the likelihood of unexpected content changes when sharing models (and may simplify use of alternative version control tools, such as git). The textual format similarly promises to enable greater interoperability between tool vendors. The planned AADL library for SysMLv2 may enable direct use of ACVIP analysis tools on SysML models, without a need for translators and alternative modeling environments.

The features of SysMLv2 are encouraging, but we recommend thorough validation of SysMLv2 capabilities. The DoD has provided a SysMLv1 to SysMLv2 conversion plan (Hettema, 2023), but the DoD and/or Army should invest in specific pilot studies of SysMLv2 to determine whether it will add efficiency to future OSVDs, particularly with regard to model-based analysis for ACVIP.

Many of the ACVIP analysis tools available through CAMET, OSATE, and other sources will require adaptation to operate on SysMLv2 models. The Army should invest in the sustainment and transition of ACVIP analysis tools to ensure they are available to reduce architecture risk in future programs.

Model-Based Test Harnesses for Acquisition

We attended many discussions of MBSE approaches between PMO FARA and the FARA Performers. Much of the discussion focused on interpretation and application of the model-based GFI provided by PMO FARA (shown in Figure 2). A significant limitation of the MBSE approach to model validation in OSVD was that it required *manual* evaluation of performer models by subject matter experts. For example, for FARA correct Performer use of an interface block to type a port in an internal block diagram was only validated by manual review by SMEs and through group discussion. An automated validation approach, such as the model-based test harnesses we demonstrated in our recent study (Smith, Whillock, Edman, Lewis, & Vestal, 2018), could significantly reduce the effort required by enabling performers to self-validate. We encourage the Army to invest in such capabilities to streamline future uses of model-based GFI.

Time Sensitive Networking

There is a clear trend toward Time Sensitive Networking (TSN) in DoD aviation systems. MBSE tools, particularly tools like SysML which describe system configuration and tools like OSATE and FASTAR which analyze network configuration should be updated and expanded to provide better support for TSN. The current industry landscape relies on proprietary tools, which were a common source of errors and confusion during OSVD.

13. Conclusion

OSVD was a learning experience for all parties involved. As discussed in this report, we experienced challenges, particularly when accessing, exchanging, or interpreting digital engineering artifacts across organizational boundaries. Major shifts in culture in both Government and industry are slowly but surely taking hold.

We recommend strategic investments by the Army and industry to streamline inter-organizational access to engineering artifacts, leverage semantically precise models for planning purposes, and allocate sufficient schedule to pivot when model-based analysis reveals new risks. Continuing to invest in these capabilities and approaches will drive culture change.

The FARA OSVD was a significant step forward in practical application and verification of MOSA. We observed first-hand how FARA performers leaned in to model-based engineering, open architectures, interoperability, virtual integration, model-based analysis, and collaboration with third parties. Despite FARA's cancellation, we ended our involvement in OSVD encouraged by the direction in which Army aviation is headed.

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Appendix A: Acronyms

- AADL – Architecture Analysis and Design Language
- ACVIP – Architecture Centric Virtual Integration Process
- AI – Artificial Intelligence
- ARINC – Aeronautical Radio Incorporated
- ASM - Aircraft Systems Monitoring
- AvMC – Aviation and Missile Center
- AVS - Air Vehicle System
- CAMET – Curated Access to Model-based Engineering Tools
- CMU – Carnegie Mellon University
- COP – Common Operating Picture
- CPS – Cyber-Physical System
- CSCI - Computer Software Configuration Item
- DAL - Design Assurance Levels
- ECBU – Electronic Circuit Breaker Unit
- EGI – Embedded GPS/INS
- ELAN - Enterprise Local Area Network
- Eval - Evaluation
- FACE – Future Airborne Capability Environment
- FARA – Future Attack and Reconnaissance Aircraft
- GFE – Government Furnished Equipment
- GFI – Government Furnished Information
- HUMS - Health and Usage Monitoring System
- ICD: Interface Control Document
- LAD – Large Area Display
- MACC - Miniature Airborne Communications Converter
- MAST - Modeling and Analysis Suite for Real-Time Applications
- METAL-V - Model-Based Engineering Tools for an Affordable Lifecycle – Vertical
- ML – Machine Learning
- MOSA – Modular Open Systems Approach
- OEM – Original Equipment Manufacturer
- OSVD – Open Systems Verification Demonstration
- PSSS – Platform Specific Services Segment
- S3I - Software, Simulation, Systems Engineering and Integration Directorate
- SA – Situational Awareness
- SDD: Software Design Document
- SNC – Sierra Nevada Corporation
- SPICA - Separation Platform for Integrating Complex Avionics
- SUA – System Under Assessment
- SysML – Systems Modeling Language
- TDP – Technical Data Package

- TPI – Third Party Integrator
- TSN – Time Sensitive Networking
- USB – Universal Serial Bus
- VMC – Vehicle Management Computer
- WCA – Warning, Caution Advisory